A Constraint on the Distance Scale to Cosmological Gamma–Ray Bursts

Jean M. Quashnock[1]

Department of Astronomy and Astrophysics
University of Chicago, Chicago, Illinois 60637

If γ–ray bursts have a cosmological origin, the sources are expected to trace the large–scale structure of luminous matter in the universe. I use a new likelihood method that compares the counts–in–cells distribution of γ–ray bursts in the BATSE 3B catalog with that expected from the known large–scale structure of the universe, in order to place a constraint on the distance scale to cosmological bursts. I find, at the 95% confidence level, that the comoving distance to the "edge" of the burst distribution is greater than 630 h^{-1} Mpc ($z > 0.25$), and that the nearest burst is farther than 40 h^{-1} Mpc. The median distance to the nearest burst is 170 h^{-1} Mpc, implying that the total energy released in γ–rays during a burst event is of order $3 \times 10^{51}\ h^{-2}$ erg. None of the bursts that have been observed by BATSE are in nearby galaxies, nor is a signature from the Coma cluster or the "Great Wall" likely to be seen in the data at present.

INTRODUCTION

The origin of γ–ray bursts is still unknown and is currently the subject of a "great debate" in the astronomical community. Do the bursts have a galactic origin (1) or are they cosmological (2) ? And what is their distance scale?

In this paper, I do not attempt to answer the first question, but rather, I show that *if* one assumes that γ–ray bursts are cosmological in origin, one can begin to answer the second question and place a constraint on the distance scale to the bursts. This is because cosmological bursts are expected to trace the large–scale structure of luminous matter in the universe (3) . The constraint comes from comparing the *expected* clustering pattern of bursts on the sky — which will depend on their distance scale because of projection effects — with that *actually observed*. The observed angular distribution is in fact quite isotropic (4) ; hence, only a lower limit to the distance scale can be placed because a sufficiently large distance will always lead to a sufficiently isotropic distribution on the sky.

Here I use a powerful new likelihood method (5) , which I had previously developed to analyze repeating of γ–ray bursts in the BATSE 1B and 2B

[1] *Compton* GRO Fellow

catalogs (6) , to compare the observed counts–in–cells distribution in the new BATSE 3B catalog (7) with that expected for bursts at cosmological distances.

Here I will assume for simplicity that $\Omega_0 = 1$ and $\Lambda = 0$, and that the large–scale structure clustering pattern is constant in comoving coordinates. The results are in fact insensitive to these assumptions because of the small redshifts that are involved. I follow the usual convention and take h to be the Hubble constant in units of 100 km s^{-1} Mpc^{-1}.

LIKELIHOOD METHOD

Let $N_{\rm cell}$ be a large number of circular cells, each centered on a random position on the sky. Each cell is of fixed solid angle size $\Omega = 2\pi(1-\cos\theta_{\rm rad})$, where $\theta_{\rm rad}$ is the angular radius of the cell. I set the number of cells to be such that any part of the sky is covered, on average, by one cell; hence, $N_{\rm cell} = 4\pi/\Omega$. Let C_N to be the number of these cells having N γ–ray bursts in them, out of the $N_{\rm tot} = 1122$ in the BATSE 3B catalog, where $N = 0, 1, 2, ...$ I then define the observed counts–in–cells distribution, $P_N \equiv C_N/N_{\rm cell}$, as the probability that a randomly chosen cell of size Ω has N bursts in it. The counts–in–cells distribution contains information about clustering of γ–ray bursts on scales comparable to the angular size $\theta_{\rm rad}$ of the cell.

I now define Q_N to be the counts–in–cells distribution that is expected if γ–ray bursts are cosmological in origin and trace the large–scale structure of luminous matter in the universe. This expected distribution depends on only one unknown parameter, the effective distance D to γ–ray bursts (which I define below), because the angular clustering pattern of bursts on the sky will depend by projection on this distance.

The *likelihood* $\mathcal{L}$ measures how likely it is that the observed counts–in–cells distribution P_N is drawn from the expected distribution Q_N. Since Q_N depends on the unknown effective distance D to γ–ray bursts, the likelihood is really a measure of how likely a given value of D is. I find that (5) :

$$\log\mathcal{L} = N_{\rm cell}\sum_N P_N \log Q_N + \text{constant} \ . \tag{1}$$

Now the cumulative $C_{\rm max}/C_{\rm min}$ distribution of γ–ray bursts seen by BATSE begins to roll over from a $-3/2$ power–law for bursts fainter than $C_{\rm max}/C_{\rm min} \sim 10$. Since this is many times above threshold, it suggests that BATSE sees most of the source distribution and that this distribution is not spatially homogeneous (8) . I define D as the comoving distance beyond which the source density drops appreciably. It is not the distance to the very dimmest burst in the BATSE catalog, but rather the typical distance to most of the dim bursts in the sample; thus, D is the *effective distance* to the "edge" of the source distribution in the BATSE catalog.

I take the power spectrum which characterizes the large–scale clustering of γ–ray burst sources to be the same as that determined from a redshift survey

of radio galaxies (9) . This power spectrum is characteristic of moderately rich environments, and is intermediate between that of ordinary galaxies and clusters. Because the exact bias factor relating the clustering of γ–ray burst sources to that of luminous matter is unknown, such an intermediate ansatz is reasonable. In any case, the resultant distance limit depends only weakly on the bias factor (roughly as the square root).

Knowledge of the power spectrum permits a calculation of the expected angular clustering pattern, the expected counts–in–cells distribution Q_N, and finally the likelihood $\mathcal{L}$ [from equation (1)], all as a function of the effective distance D to γ–ray bursts (5). I have included the smearing due to finite positional errors on the clustering on small scales (10) . Indeed, each burst in the BATSE catalog is assigned a positional uncertainty $\theta_{\rm err}$ corresponding to a 68% confidence that the true burst position is within an angle $\theta_{\rm err}$ to the position listed in the catalog.

I have chosen the cell size $\theta_{\rm rad}$ in order to maximize the sensitivity of detection, or signal–to–noise, given the strength of the signal expected. For a sample of 1122 bursts (the total number of bursts in the BATSE 3B catalog) with positional smearing of $\theta_{\rm err} = 3.8^\circ$ (the median value in the 3B catalog), the signal–to–noise is maximized when cells of $\theta_{\rm rad} = 5^\circ$ are used (5) .

RESULTS

Figure 1 shows the likelihood of the BATSE 3B catalog data as a function of the effective comoving distance D, calculated using cells of size $\theta_{\rm rad} = 5^\circ$. The likelihood is normalized to that expected for an isotropic distribution on the sky. At large values of D (the maximum value allowed is $D = R_{\rm H} = 6000\ h^{-1}$ Mpc, the size of the horizon in a closed universe), the likelihood goes to unity, because by projection a sufficiently large distance will always lead to an isotropic distribution on the sky. Note also that there is no value of D for which the likelihood is greater than 1; thus, the maximum likelihood value for D is $R_{\rm H}$ and the 3B data are consistent with isotropy.

The solid line in Fig. 1 shows the likelihood for a positional smearing of $\theta_{\rm err} = 3.8^\circ$, corresponding to the median value in the 3B catalog. To illustrate the dependence of these results on positional errors, I also show (dashed line) the results for a larger positional smearing[2] of $\theta_{\rm err} = 6.6^\circ$ (with cells of size $\theta_{\rm rad} = 9^\circ$ to maximize signal–to–noise).

Small values of the effective comoving distance to γ–ray bursts are unlikely, according to Fig. 1: I find, at the 95% confidence level, that for the 3B median positional error of $\theta_{\rm err} = 3.8^\circ$, D must be greater than 630 h^{-1} Mpc, corresponding to a redshift $z > 0.25$. If the positional errors are larger than quoted and are better characterized by $\theta_{\rm err} = 6.6^\circ$, these results are

[2]Graziani & Lamb (11) compare the 3B positions with those from the IPN network, and conclude that the systematic errors are larger than the 1.6° value quoted in the 3B catalog. Their best–fit model gives a median positional error of 6.6°.

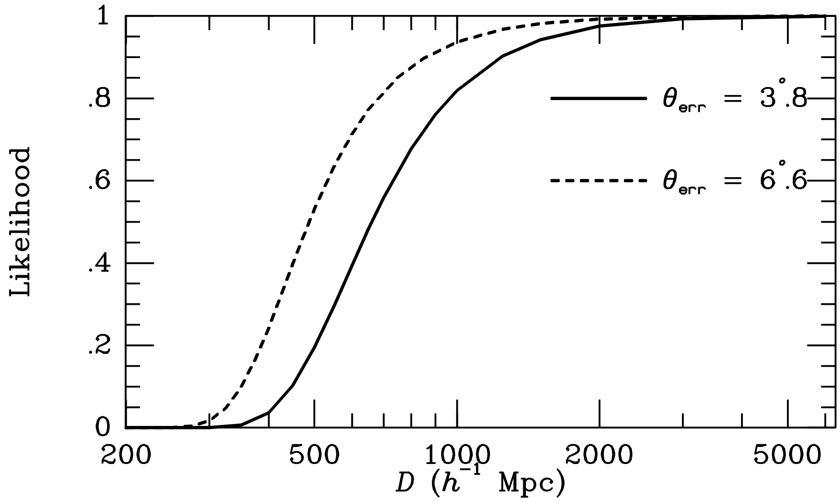

FIG. 1. The likelihood of the BATSE 3B catalog data as a function of the effective comoving distance D to γ–ray bursts, shown with a smearing of $\theta_{\rm err} = 3.8°$ and $6.6°$.

only slightly weakened: At the 95% confidence level, D must be greater than 500 h^{-1} Mpc, corresponding to a redshift $z > 0.19$.

These limits are not sensitive to earlier assumptions on cosmology and clustering evolution since these only become important at higher redshifts. They are also conservative limits in that a constant median value for the positional errors was used, rather than the entire distribution of errors. This is because the bright bursts, which ostensibly are nearer to us, are more clustered and are responsible for the bulk of the expected signal, but in fact have smaller errors than the median value. The faint bursts, which are far away, are hardly clustered to begin with (even before smearing), but have errors larger than the median value. Hence the expected clustering pattern has been smeared more by using a constant median value (this permits a simpler calculation) than by smearing using the entire distribution of errors. So the counts–in–cells statistic has been weakened somewhat and thus the quoted lower limits are in fact conservative.

CONCLUSIONS

If γ–ray bursts are cosmological and trace the large–scale structure of luminous matter in the universe, and their positional errors are as quoted in the 3B catalog, then the lack of any angular clustering in the data implies that the observed distance to the "edge" of the burst distribution must be farther than 630 h^{-1} Mpc. Since there are 1122 bursts in the catalog, an effective

limit on the *nearest* burst to us can be placed by convoluting the likelihood as a function of D (Fig. 1) with the nearest neighbor distribution of 1122 bursts inside a sphere of radius D. I find that the nearest burst must be farther than 40 h^{-1} Mpc at the 95% confidence level, and farther than 10 h^{-1} Mpc at the 99.9% level. At this level of confidence, then, none of the bursts that have been observed by BATSE are in nearby galaxies. A signature from the Coma cluster or the "Great Wall" ($\sim 70\ h^{-1}$ Mpc) is not likely to be seen in the data at present, since only a few bursts could have originated from these distances.

The median distance to the nearest burst is 170 h^{-1} Mpc. Since the brightest burst in the 3B catalog has a fluence of 7.8×10^{-4} erg cm^{-2} in γ–rays, this implies that the total energy released in γ–rays during a burst event is of order $3 \times 10^{51}\ h^{-2}$ erg.

As the number of observed γ–ray bursts keeps increasing, the distance limit will improve. In fact, with 3000 burst locations, the clustering of bursts might just be detectable (3) and would provide compelling evidence for a cosmological origin. If it is not detected, the redshift to the "edge" of the burst distribution would be put at $z \sim 1$ or beyond.

ACKNOWLEDGMENTS

I would like to acknowledge useful discussions with Carlo Graziani, Don Lamb, Cole Miller and Bob Nichol. This research was supported in part by NASA through the *Compton* Fellowship Program — grant NAG 5-2660, grant NAG 5-2868, and contract NASW-4690.

REFERENCES

1. D. Q. Lamb, Proc. Astr. Soc. Pac., (1995) (in press)
2. B. Paczyński, Proc. Astr. Soc. Pac., (1995) (in press)
3. D. Q. Lamb and J. M. Quashnock, Astrophys. J. Lett. **415**, L1 (1993)
4. M. S. Briggs et al., Astrophys. J., (1995) (in press)
5. J. M. Quashnock, Astrophys. J. Lett., (1996) (in press)
6. J. M. Quashnock, Astrophys. Sp. Sci. **231**, 35 (1995)
7. C. A. Meegan et al., Astrophys. J., (1996) (submitted)
8. C. A. Meegan et al., Nature **355**, 143 (1992)
9. J. A. Peacock and D. Nicholson, Mon. Not. Roy. Astr. Soc. **253**, 307 (1991)
10. D. H. Hartmann, E. V. Linder and G. R. Blumenthal., Astrophys. J. Lett. **367**, 186 (1991)
11. C. Graziani and D. Q. Lamb, these proceedings